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Acoustic Analysis of Lexical Tone in Mandarin Infant-Directed Speech

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Using Mandarin Chinese, a "tone language" in which the pitch contours of syllables differentiate words, the authors examined the acoustic modifications of infant-directed speech (IDS) at the syllable level to test 2 hypotheses: (a) the overall increase in pitch and intonation contour that occurs in IDS at the phrase level would not distort lexical pitch at the syllable level and (b) IDS provides exaggerates cues to lexical tones. Sixteen Mandarin-speaking mothers were recorded while addressing their infants and addressing an adult. The results indicate that IDS does not distort the acoustic cues that are essential to word meaning at the syllable level; evidence of exaggeration of the acoustic differences in IDS was observed, extending previous findings of phonetic exaggeration to the lexical level.

Keywords: infant-directed speech, Mandarin Chinese, lexical tone, acoustic analysis

Progress has been made in understanding *infant-directed speech* (IDS), the speech style used by adults when addressing infants (e.g., Ferguson, 1964; Fernald & Simon, 1984; Snow, 1972; Stern, Spieker, & Mackain, 1982). Linguistically, IDS exhibits frequent repetition and simplified syntax, semantics, and phonology when compared with *adult-directed speech* (ADS; Cross, 1977; Snow, 1972). Acoustically, IDS is easily recognized because of its unique prosodic pattern, which includes a slower tempo, higher average pitch, and exaggerated intonation contours (Fernald & Simon, 1984; Grieser & Kuhl, 1988; Stern et al., 1982). Prosodic modifications in IDS may facilitate communication development by eliciting attention and positive affect during adult–child interaction (Cooper & Aslin, 1990; Fernald & Kuhl, 1987; Papousek, Papousek, & Symmes, 1991; Werker & McLeod, 1989).

Studies have demonstrated that critical acoustic–phonetic features are exaggerated in IDS and that this too may assist communicative development. Spectrographic analysis of the vowels /i/, /a/, and /u/ in mothers' IDS and ADS showed an acoustically expanded *vowel triangle* in which the acoustic differences among vowels is expanded (Burnham, Kitamura, & Vollmer-Conna, 2002; Kuhl et al., 1997). Liu, Kuhl, and Tsao (2003) replicated the expanded IDS vowel triangle in a tonal language, Mandarin Chinese, and found a positive association between the degree of vowel exaggeration in IDS and infants' speech discrimination performance in the 1st year of life. These findings add support to the hypothesis that IDS plays an important role in infants' early speech development.

The present study extended previous investigations by examining how IDS affects a suprasegmental dimension, lexical tone. In Mandarin Chinese, every syllable must carry a lexical tone, an element that serves to signify lexical meaning. There are four tones in Mandarin: a high-level tone (Tone 1, ˥), a mid-rising tone (Tone 2, ˧˥), a low-dipping tone (Tone 3, ˨˩˦), and a high-falling tone (Tone 4, ˥˩).

The acoustic correlates of Mandarin tones are pitch height and pitch contour (Howie, 1976; Tseng, 1990; Wu, 1986). Duration also differs; Tone 3 is typically the longest and Tone 4 the shortest, both in citation form and spontaneous speech (Lin, 1965; Tseng, 1990). Another temporal feature, one that is relational, is the *turning point*, the point in time at which the pitch contour changes from falling to rising. The turning point helps differentiate Tone 2 from Tone 3 (Dreher & Lee, 1966; Wang, Jongman, & Sereno, 2003). Perceptual studies on Mandarin-speaking adults indicate that pitch height and pitch contour range are the most important acoustic components, with temporal features playing a secondary role (Blicher, Diehl, & Cohen, 1990; Gandour, 1984; Howie, 1976; Massaro, Cohen, & Tseng, 1985; Moore & Jongman, 1997; Shen & Lin, 1991; Tseng, 1990).

Previous studies have shown that mothers who speak tonal languages (e.g., Mandarin, Thai) use IDS—mothers elevate the average pitch and expand the pitch contour range over phrases and sentences (Grieser & Kuhl, 1988; Kitamura, Thanavishuth, Burnham, & Luksaneeyanawin, 2002). Previous authors have noted the interesting issue this raises: Because pitch height and pitch contour at the syllable level are essential for lexical meaning, an overall increase and exaggeration in pitch contour at the phrase level could distort the acoustic correlates of lexical tone, creating difficulty for infants learning tones (Papousek & Hwang, 1991; Papousek et al.,

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1991). Kitamura et al. (2002) reported that the higher pitch of Thai IDS did not negatively affect the perceptual judgment of lexical tone in Thai for adults. There has been no data examining syllable-level tone modifications in Mandarin IDS.

The present study looked at Mandarin IDS at the syllable level to examine how Mandarin-speaking mothers modify the acoustic correlates of lexical tones when addressing their 10–12-month-old infants. We tested two hypotheses. First, we hypothesized that the primary acoustic correlates distinguishing lexical tone—pitch height, pitch range, duration, and turning point—would not be distorted or obscured by the overall increase in pitch that has previously been observed in Mandarin IDS (e.g., Grieser & Kuhl, 1988). Testing this hypothesis involved examination of the pitch height, pitch range, duration, and turning points to verify that the critical cues responsible for their differentiation are preserved in IDS.

Second, following previous studies on vowels (Burnham et al., 2002; Kuhl et al., 1997; Liu et al., 2003), we hypothesized that pitch height differences, pitch range differences, and durational differences in IDS would be exaggerated in comparison with ADS, making IDS tones potentially more easily distinguished by infants. To accomplish this goal, we needed to examine whether the pitch height, range, and duration measures in IDS were greater than those in ADS. To this end, we used psychoacoustic studies of intonation to guide our analyses. It has been argued in the psychoacoustics literature that, even for complex tones, the perception of intonation is best characterized by the use of an *equivalent-rectangular-bandwidth-rate* (ERB) scale (Glasberg & Moore, 1990; Hermes & van Gestel, 1991). Typically, in intonation research, intonation change is described using a linear scale (*Hz*) or, more recently, a scale that combines logarithmic units (*Bark* scale [Zwicker & Terhardt, 1980]; *Mel* scale [Stevens, Volkman, & Newman, 1937]; *Semitone* scale [Rietveld & Gussenhoven, 1985]). However, more recent research suggests that intonation is best characterized by the ERB scale (Hermes & van Gestel, 1991). The ERB scale represents the frequency selectivity (i.e., the critical band) of the auditory system and is intermediate between a linear and a logarithmic scale for frequencies below 500 Hz (Glasberg & Moore, 1990). We tested the exaggeration hypotheses using both the more historically familiar Hz scale and the recently validated ERB scale. Psychoacoustic data allow us to better interpret the perceptual value of the acoustic modifications made in IDS.

Method

Participants

Sixteen mother–infant dyads, with infants (10 boys, 6 girls) 10–12 months of age, participated in the speech recordings. Infants were recruited from the infant list of the House Registry Office of Kaohsuing City in Taiwan. The inclusion criteria for mothers were: (a) Mandarin Chinese was their only or dominant language; (b) they were their infant's primary caregiver; and (c) they had no known physical, sensory, mental, or language deficits. The socioeconomic status (SES) of both of each infant's parents was checked with an SES background questionnaire in Chinese that measured parental occupation, income, and education. As indicated by this SES questionnaire, the infants were mostly recruited from middle-class families. All mothers were high school or 4-year-college graduates (M = 13.55 years, SD = 1.86), and the fathers had similar educational backgrounds (M = 13.27 years, SD = 1.62). Most of the mothers worked as service providers, and the majority of fathers worked as technicians.

Speech Recording Procedure

Mothers' IDS and ADS samples were audiorecorded in a sound-attenuated booth via a digital tape recorder. Mothers were told that the investigation focused on natural interaction and play and were recorded during IDS while interacting with their infants. During ADS, mothers talked with the experimenter about their infant's interest in the toys and pictures that were supplied to elicit the target words (see below). The toys and pictures were labeled with the target words for the mothers to use. The recording sequence of IDS and ADS was counterbalanced across participants.

Target Words

Twelve Mandarin Chinese bisyllabic words served as the target words. They were (C)VCV(V) in form. The tone pattern of the second syllable in the target words was always the high flat tone (Tone 1). The appropriate tone numeral was attached to each syllable (e.g., /i1ʂɚ˞1/, *doctor*; /i2ma1/, *aunt*). The four tones each occurred with three vowels (/i/, /a/, and /u/) to create the 12 bisyllabic words (4 tones × 3 vowels).

Acoustic Analysis

Excluding target words that overlapped with conversation from the experimenter, infant vocalizations, or toy noise, we used the first two clear tokens of each target word for acoustic analysis using the Kay Elemetrics Computerized Speech Lab (CSL) software (KayPENTAX, Lincoln Park, NJ). Speech samples were low-pass filtered at 10 kHz.

Acoustic Measures

Fundamental Frequency (F0)

F0 values were extracted using the autocorrelation algorithm of CSL. F0 values were printed for each 20 ms of the vowel.

Mean F0. Mean F0 values for each vowel were calculated for each mother's IDS and ADS. Mean F0 defines the pitch height of individual tones.

F0 range. The highest (peak) and lowest (valley) pitch points were measured for each tone. The F0 range (peak − valley) indicated the pitch contour excursion of individual tones.

Duration

Vowel onsets were marked when both F1 and F2 became visible on the spectrogram. Vowel offsets were marked at the point where F2 and/or F1 were no longer visible. Each tone's duration was measured from vocalic onset to offset. In addition, the relative timing of the point where the pitch contour changed from falling to rising, the turning point, was calculated as follows:

$$\text{relative turning point} = (\text{duration of onset to valley} \div \text{duration of vowel}) \times 100\%.$$

Measure Reliability

The interrater reliability of acoustic measures was calculated on a randomly selected 10% of the target tokens by a second investigator, who was well trained in acoustic analysis. Interrater reliability was high ($r = .90$).

Results

Figure 1 plots the average acoustic correlates for the four lexical tones in ADS and IDS observed in the present study.

Mean F0

Figure 2 illustrates the mean F0 in Hz for each lexical tone in ADS and IDS. As expected, the mean F0 was higher in IDS (M = 270.91 Hz, SE = 9.11) than in ADS (M = 209.86 Hz, SE = 5.48), $F(1, 15) = 114.56$, $p < .001$, $\eta_p^2 = .884$. Separate one-way repeated measure analyses of variance (ANOVAs) for IDS and ADS evaluated tone effects on mean F0. F0 varied significantly with lexical tones for ADS, $F(3, 45) = 30.38$, $p < .001$, $\eta_p^2 = .669$, as well as ID speech, $F(3, 45) = 37.81$, $p < .001$, $\eta_p^2 = .716$. Evidence of preservation of the information critical to lexical tone at the syllable level is whether the same order of intrinsic pitch occurs in IDS and ADS. Least significant difference (LSD) post hoc comparisons ($p < .001$) showed that the same order of intrinsic pitch occurred across the two speech styles: Tone 1 ≈ Tone 4 > Tone 2 > Tone 3.

To test the exaggeration hypothesis, we carried out a paired-sample one-tailed t test for pitch differences among tone pairs in ADS versus IDS, which showed that spectral differences between tones were greater in IDS: Tone 1 versus Tone 3, $t(15) = -3.53$, $p = .002$; Tone 2 versus Tone 3, $t(15) = -3.57$, $p = .002$; Tone 2 versus Tone 4, $t(15) = -2.89$, $p = .005$; and Tone 4 versus Tone 3, $t(15) = -5.11$, $p < .001$. Converting the Hz values to the ERB scale produced significant effects for Tone 1 versus Tone 3, $t(15) = -3.82$, $p = .001$; Tone 2 versus Tone 3, $t(15) = -3.73$, $p = .001$, and Tone 4 versus Tone 3, $t(15) = -2.84$, $p = .006$.

The results indicate that in spite of an overall rise in pitch in Mandarin IDS, which has been observed previously (Grieser & Kuhl, 1988), IDS preserves the pitch height feature that specifies lexical tone differences and is important for perceptually distinguishing tones (e.g., Gandour, 1984). Moreover, comparisons of ADS and IDS using both the conventional Hz measure and the ERB scale measure indicate that IDS exaggerates the pitch height differences between tone pairs.

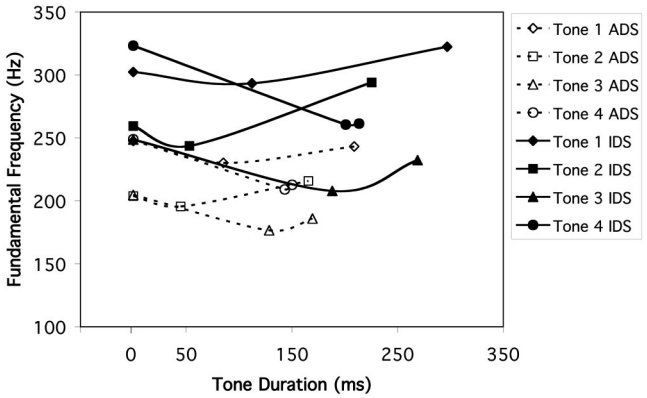

Figure 1. Average acoustic correlates (F0, F0 range, tone duration, and turning point) of Mandarin tones in adult-directed speech (ADS) and infant-directed speech (IDS).

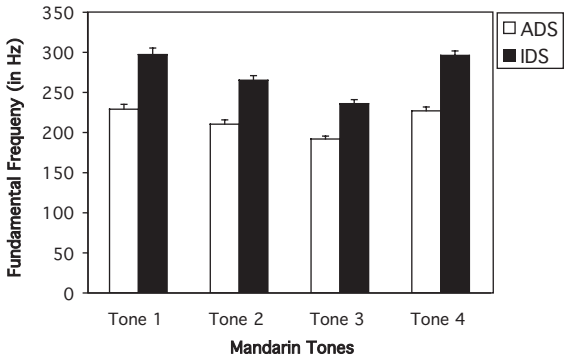

Figure 2. Mean F0 of each Mandarin tone in adult-directed speech (ADS) and infant-directed speech (IDS). Error bars represent standard errors.

F0 Range

Figure 3 illustrates the average F0 range of each tone in ADS and IDS. A 2-way ANOVA comparing IDS and ADS showed a significant main effect of range, with IDS showing significantly greater pitch range, $F(1, 15) = 62.65$, $p < .001$, $\eta_p^2 = .807$. The Speech Style × Tone interaction was not significant, $F(3, 45) = 1.94$, $p > .10$, suggesting preservation of the important cues to lexical tones. Post hoc analyses showed a similar sequence of F0 range for tones in ADS (Tone 4 ≈ Tone 3 > Tone 2 ≈ Tone 1) and IDS (Tone 4 ≈ Tone 3 > Tone 2 > Tone 1).

To examine the exaggeration hypothesis, we tested the differences between the steady tone (Tone 1) and other tones to see if the range increase in IDS could potentially be helpful. On the Hz scale, the F0 range of IDS was significantly increased in a paired-sample one-tailed t test over ADS for Tone 1 versus Tone 4, $t(15) = 2.49$, $p = .015$, and Tone 1 versus Tone 3, $t(15) = 1.01$, $p = .009$. When represented on the ERB scale, the F0 range was

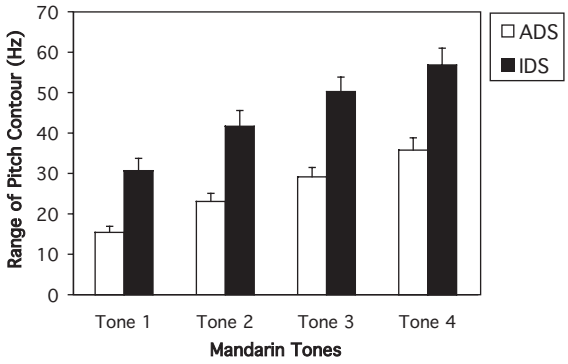

Figure 3. Average F0 ranges of pitch contour of each Mandarin tone in adult-directed speech (ADS) and infant-directed speech (IDS). Error bars represent standard errors.

significantly increased for the additional contrast of Tone 1 versus Tone 2, $t(15) = -1.77$, $p = .043$, and marginally significant for Tone 1 versus Tone 3, $t(15) = -1.68$, $p = .057$, and Tone 1 versus Tone 4, $t(15) = -1.51$, $p = .076$.

The results suggest that Mandarin-speaking mothers preserve the order of pitch range cues in IDS at the syllable level that are important to lexical tone. In addition, the larger range differences (measured in both the Hz and the ERB scale) of F0 range between the high-level tone (Tone 1) and other contour tones (Tones 2, 3, and 4) in IDS suggests an exaggeration of F0 contour pattern in IDS as compared with ADS.

Lexical Tone Duration

Lexical tone durations for Mandarin ADS and IDS are illustrated in Figure 4. Lexical tone duration in IDS ($M = 251.25$ ms, $SE = 10.10$) was significantly longer than that in ADS ($M = 173.67$ ms, $SE = 5.91$), $F(1, 15) = 59.43$, $p < .001$, $\eta_p^2 = .798$. In ADS, tone duration varied with tone pattern, $F(3, 45) = 24.15$, $p < .001$, $\eta_p^2 = .617$, and showed the following order: Tone 1 > Tone 3 ≈ Tone 2 > Tone 4 (LSD post hoc test, $p < .05$). In IDS, duration also varied with tone, $F(3, 45) = 9.03$, $p < .001$, $\eta_p^2 = .376$, and the same order was seen: Tone 1 ≈ Tone 3 > Tone 2 > Tone 4 ($p < .05$). Thus, mothers preserved the duration cue at the syllable level in IDS.

To test the exaggeration hypothesis, we carried out a one-tailed *t* test on the duration differences among lexical tone pairs in ADS and IDS, which showed that the duration differences between Tones 2 and 3, $t(15) = -2.35$, $p = .033$, and Tones 3 and 4, $t(15) = -2.66$, $p = .018$, were larger in IDS. Data on the just noticeable difference for duration of tones in a continuous tone sequence that are pertinent to the current study indicate that a 7-ms difference is discriminable for adults (Friberg & Sundberg, 1995). The magnitude of the difference in duration in ADS between Tone 2 and Tone 3 (3.85 ms) would therefore not provide a reliable cue for discrimination. However, the durational difference between Tone 2 and Tone 3 in IDS (43.55 ms) was well beyond the threshold for detection of a difference. This may be particularly important for infants, given that these two tones have a similar pitch pattern and are difficult to distinguish (Blicher et al., 1990; Wang et al., 2003).

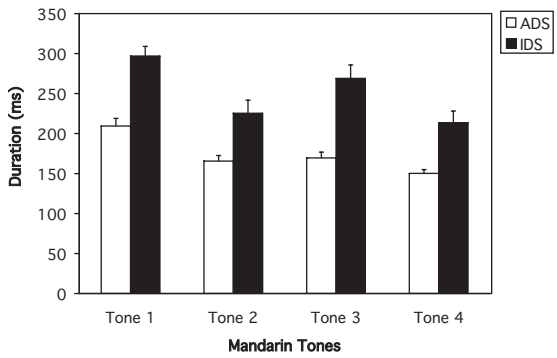

Figure 4. Mean duration of each Mandarin tone in adult-directed speech (ADS) and infant-directed speech (IDS). Error bars represent standard errors.

Turning Point

The results show that duration increased significantly in IDS as opposed to ADS, and this raises an interesting issue regarding the turning point in IDS. In ADS, the turning point distinguishes Tone 2 and Tone 3, and we predicted that it would also do so in IDS; however, we predicted that IDS would not exaggerate the turning point because the turning point is defined proportionally, and exaggerating this cue could perceptually confuse infants.

The F0 turning points in ADS and IDS are illustrated in Figure 5. As predicted, there was no significant style difference, $F(1, 15) < 1$, and there was a significant tone effect, $F(3, 45) = 144.87$, $p < .001$, $\eta_p^2 = .906$, indicating that both ADS and IDS preserve the turning point. Post hoc comparisons (LSD test, $p < .05$) showed the same order for F0 turning point in ADS and IDS: Tone 4 > Tone 3 > Tone 1 > Tone 2. This result is consistent with previous findings that the turning point of Tone 2 occurs earlier than that of Tone 3 (Dreher & Lee, 1966; Wang et al., 2003).

Discussion

This study examined the acoustic characteristics of lexical tones in Mandarin Chinese IDS and ADS to explore the modifications made by mothers when engaged in interaction with their preverbal infants. We tested two hypotheses. First, we hypothesized that the modifications inherent in IDS across cultures—that is, the higher overall pitch that has been observed at the level of the phrase or sentence (see Grieser & Kuhl, 1988, for Mandarin Chinese; Kitamura et al., 2002, for Thai)—would not distort or obscure lexical pitch at the syllable level, which is essential for the preservation of lexical meaning. Second, we explored whether Mandarin IDS provided any evidence of phonetic exaggeration, as has previously been observed in IDS for vowels (Burnham et al., 2002; Kuhl et al., 1997; Liu et al., 2003).

Our results provide support for both hypotheses: Mandarin-speaking mothers preserve the spectral and temporal correlates of lexical tones that are necessary to convey the correct lexical meaning of each syllable in IDS. In addition, the overall pattern of results suggests that Mandarin IDS exaggerates features of the tones that could potentially make them more distinct for infants. The latter finding is consistent with previous results indicating that IDS emphasizes phonetically relevant differences.

Regarding the first hypothesis, our results confirm that lexical tones in IDS, as compared with ADS, exhibit an overall higher pitch and an overall expansion in the F0 range of pitch contours but that among the four tones, the relative order of pitch height and pitch range is parallel in the two speech styles. These findings show that the overall rise in pitch that occurs in IDS does not distort or obscure the spectral patterns necessary for the identification of lexical tones. Moreover, as hypothesized, a relational temporal feature that is critical for differentiating Tone 2 and Tone 3 (Wang et al., 2003)—the relative timing of the F0 turning point—is preserved in IDS. When expanding the durational differences in IDS tones, mothers proportionally adjust the turning point to maintain the relative point at which the direction of pitch is changed, thus preserving a critical feature that is essential for perceptually identifying lexical tones and word meanings (Dreher & Lee, 1966; Leather, 1983).

Regarding the second hypothesis, the results show that the spectral differences among tones—the pitch height differences, the

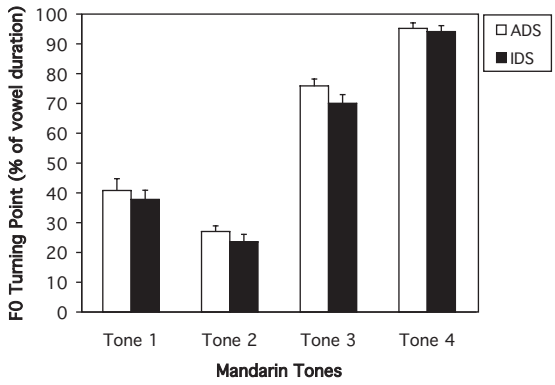

Figure 5. Timing of F0 turning points of each Mandarin tone in adult-directed speech (ADS) and infant-directed speech (IDS). Error bars represent standard errors.

F0 range differences, and the durational differences among tones—were more distinct in IDS than in ADS. These findings suggest that the hypothesis that IDS involves phonetic exaggeration (Burnham et al., 2002; Kuhl et al., 1997; Liu et al., 2003) can be generalized to lexical tones at the syllable level in a tonal language.

Can the phonetic information in IDS facilitate infant language development? The acoustic exaggeration of phonetic units may play a beneficial role by increasing infant attention to the critical properties in native-language speech and by increasing infants' abilities to distinguish phonetic units. Liu et al. (2003) demonstrated an association between the degree of mothers' acoustic exaggeration of speech and infants' performance in phonetic discrimination tests in the laboratory. Liu et al. showed in two independent samples of infants (one 6–8 months of age and the other 10–12 months of age) that infants whose mothers exaggerated the acoustic changes in vowels in IDS to a greater degree showed correspondingly better performance in infant speech discrimination tests. Furthermore, several studies have now shown that infants' abilities to perform in speech perception tasks at 6–8 months of age predicts the rate of language growth between 11 and 30 months (Kuhl, Conboy, Coffey-Corina, Padden, Rivera-Gaxiola, & Nelson, in press; Kuhl, Conboy, Padden, Nelson, & Pruitt, 2005; Rivera-Gaxiola, Klarman, Garcia-Sierra, & Kuhl, 2005; Tsao, Liu, & Kuhl, 2004) and 4–6 years of age (Newman, Ratner, Jusczyk, Jusczyk, & Dow, 2006). The phonetic exaggeration seen in IDS may thus support language development.

In the present case, augmentation of the spectral differences among lexical tones found here may make individual lexical tones perceptually more distinct from one another for infants. Infants may therefore more easily learn to associate the proper tone pattern with individual words. More distinctive tone patterns may also facilitate infant detection of the boundaries in continuous speech between words, helping preverbal infants to segment continuous speech into possible words (e.g., Jusczyk, 1997; Kooijman, Haqoort, & Cutler, 2005).

In summary, we have demonstrated that Mandarin IDS preserves the lexical tone differences seen in ADS that have been shown to be critical to their differentiation. Moreover, our data indicate that lexical tone differences in Mandarin IDS are exaggerated, potentially assisting infant tone learning. IDS may thus provide an environmental factor that accounts for some of the variance observed in young infants' phonetic abilities and, therefore, some of the variance in initial language development.

References

Blicher, D. L., Diehl, R. L., & Cohen, L. B. (1990). Effects of syllable duration on the perception of the Mandarin tone2/tone3 distinction: Evidence of auditory enhancement. *Journal of Phonetics, 18,* 37–49.

Burnham, D., Kitamura, C., & Vollmer-Conna, U. (2002, May 24). What's new, pussycat? On talking to babies and animals. *Science, 296,* 1435.

Cooper, R. P., & Aslin, R. N. (1990). Preference for infant-directed speech in the first month after birth. *Child Development, 61,* 1584–1595.

Cross, T. G. (1977). Mothers' speech adjustment: The contributions of selected child listener variables. In C. E. Snow & C. A. Ferguson (Eds.), *Talking to children: Language input and acquisition* (pp. 151–188). Cambridge, England: Cambridge University Press.

Dreher, J. J., & Lee, P. C. (1966). *Instrumental investigation of single and paired Mandarin tonemes* (Research Communication No. 13). Huntington Beach, CA: Advanced Research Laboratory, Douglas Aircraft Company.

Ferguson, C. A. (1964). Baby talk in six languages. *American Anthropologist, 66,* 103–114.

Fernald, A., & Kuhl, P. K. (1987). Acoustic determinants of infant preference for motherese speech. *Infant Behavior and Development, 10,* 279–293.

Fernald, A., & Simon, T. (1984). Expanded intonation contours in mothers' speech to newborns. *Developmental Psychology, 20,* 104–113.

Friberg, A., & Sunberg, J. (1995). Time discrimination in a monotonic, isochronous sequence. *Journal of the Acoustical Society of America, 98,* 2524–2531.

Gandour, J. T. (1984). Tone dissimilarity judgments by Chinese listeners. *Journal of Chinese Linguistics, 12,* 235–261.

Glasberg, B. R., & Moore, B. C. J. (1990). Derivation of auditory filter shapes from notched-noise data. *Hearing Research, 47,* 103–113.

Grieser, D. L., & Kuhl, P. K. (1988). Maternal speech to infants in a tonal language: Support for universal prosodic feature in motherese. *Developmental Psychology, 24,* 14–20.

Hermes, D. J., & van Gestel, J. C. (1991). The frequency scale of speech intonation. *Journal of the Acoustical Society of America, 90,* 97–102.

Howie, J. M. (1976). *Acoustical studies of Mandarin vowels and tones.* Cambridge, England: Cambridge University Press.

Jusczyk, P. W. (1997). *The discovery of spoken language.* Cambridge, MA: MIT Press.

Kitamura, C., Thanavishuth, C., Burnham, D., & Luksaneeyanawin, S. (2002). University and specificity in infant-directed speech: Pitch modifications as a function of infant age and sex in a tonal and non-tonal language. *Infant Behavior and Development, 24,* 372–392.

Kooijman, V., Haqoort, P., & Cutler, A. (2005). Electrophysiological evidence for prelinguistic infants' word recognition in continuous speech. *Brain Research: Cognitive Brain Research, 24,* 109–116.

Kuhl, P. K., Andruski, J. E., Chistovich, I. A., Chistovich, L. A., Kozhevnikova, E. V., Ryskina, V. L., et al. (1997, August 1). Cross-language analysis of phonetic units in language addressed to infants. *Science, 277,* 684–686.

Kuhl, P. K., Conboy, B. T., Coffey-Corina, S., Padden, D., Rivera-Gaxiola, M., & Nelson, T. (in press). Phonetic learning as a pathway to language: New data and native language magnet theory expanded (NLM-e). *Philosophical Transactions of the Royal Society B.*

Kuhl, P. K., Conboy, B. T., Padden, D., Nelson, T., & Pruitt, J. (2005). Early speech perception and later language development: Implications for the "critical period." *Language Learning and Development, 1,* 237–264.

Leather, J. (1983). Speaker normalization in perception of lexical tone. *Journal of Phonetics, 11,* 373–382.

Lin, M. C. (1965). The pitch indicator and the pitch characteristics of tones in standard Chinese. *Acta Acoustica (China), 2,* 8–15.

Liu, H. M., Kuhl, P. K., & Tsao, F. M. (2003). The association between mothers' speech clarity and infants' speech discrimination skill. *Developmental Science, 6,* F1–F10.

Massaro, D. W., Cohen, M. M., & Tseng, C. (1985). The evaluation and integration of pitch height and pitch contour in lexical tone perception in Mandarin Chinese. *Journal of Chinese Linguistics, 13,* 267–290.

Moore, C. B., & Jongman, A. (1997). Speaker normalization in the perception of Mandarin Chinese tones. *Journal of the Acoustical Society of America, 102,* 1864–1877.

Newman, R., Ratner, R. B., Jusczyk, A., M., Jusczyk, P. W., & Dow, K. A. (2006). Infants' early ability to segment the conversational speech signal predicts later language development: A retrospective analysis. *Developmental Psychology, 42,* 643–655.

Papousek, M., & Hwang, S. F. C. (1991). Tone and intonation in Mandarin babytalk to presyllabic infants: Comparison with registers of adult conversation and foreign language instruction. *Applied Psycholinguistics, 12,* 481–504.

Papousek, M., Papousek, H., & Symmes. D. (1991). The meanings of melodies in motherese in tone and stress language. *Infant Behavior and Development, 14,* 415–440.

Rietveld, A. C. M., & Gussenhoven, C. (1985). On the relation between pitch excursion size and prominence. *Journal of Phonetics, 13,* 299–308.

Rivera-Gaxiola, M., Klarman, L., Garcia-Sierra, A., & Kuhl, P. K. (2005). Neural patterns to speech and vocabulary growth in American infants. *NeuroReport, 16,* 495–498.

Shen, X. S., & Lin, M. C. (1991). A perceptual study of Mandarin tones 2 and 3. *Language and Speech, 34,* 145–156.

Snow, C. E. (1972). Mothers' speech to children learning language. *Journal of Child Development, 43,* 549–565.

Stern, D. N., Spieker, S., & Mackain, K. (1982). Intonation contours as signals in maternal speech to prelinguistic infants. *Developmental Psychology, 18,* 727–735.

Stevens, S. S., Volkman, J., & Newman, E. B. (1937). A scale for the measurement of the psychological magnitude pitch. *Journal of the Acoustical Society of America, 8,* 185–190.

Tsao, F. M., Liu, H. M., & Kuhl, P. K. (2004). Speech perception in infancy predicts language development in the second year of life: A longitudinal study. *Child Development, 75,* 1067–1084.

Tseng, C.-Y. (1990). *An acoustic phonetic study on tones in Mandarin Chinese.* Taipei, Taiwan: Institute of History and Philology Academia Science.

Wang, Y., Jongman, A., & Sereno, J. (2003). Acoustic and perceptual evaluation of Mandarin tone productions before and after perceptual training. *Journal of the Acoustical Society of America, 113,* 1033–1043.

Werker, J. F., & McLeod, P. J. (1989). Infant preference for both male and female infant-directed talk: A developmental study of attentional and affective responsiveness. *Canadian Journal of Psychology, 43,* 230–246.

Wu, Z. J. (1986). *The spectrographic album of mono-syllables of standard Chinese.* Beijing, China: Social Science Press.

Zwicker, E., & Terhardt, E. (1980). Analytical expressions for critical band rate and critical bandwidth as a function of frequency. *Journal of the Acoustical Society of America, 68,* 1523–1525.

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